

# PeV neutrinos from right-handed neutrino dark matter

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“Neutrino Universe”, Tetsutaro Higaki, Ryuichiro Kitano, RS,  
[arXiv:1405.0013], JHEP 1407(2014)044

# Mysteries in our universe

The standard model achieved a big success.

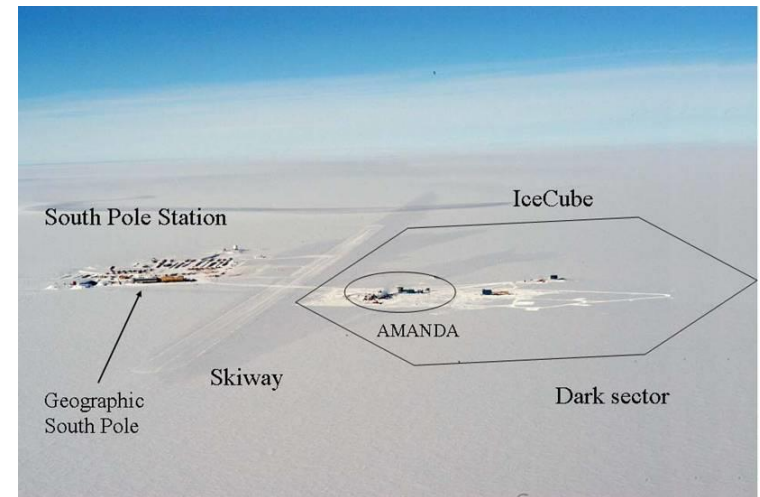
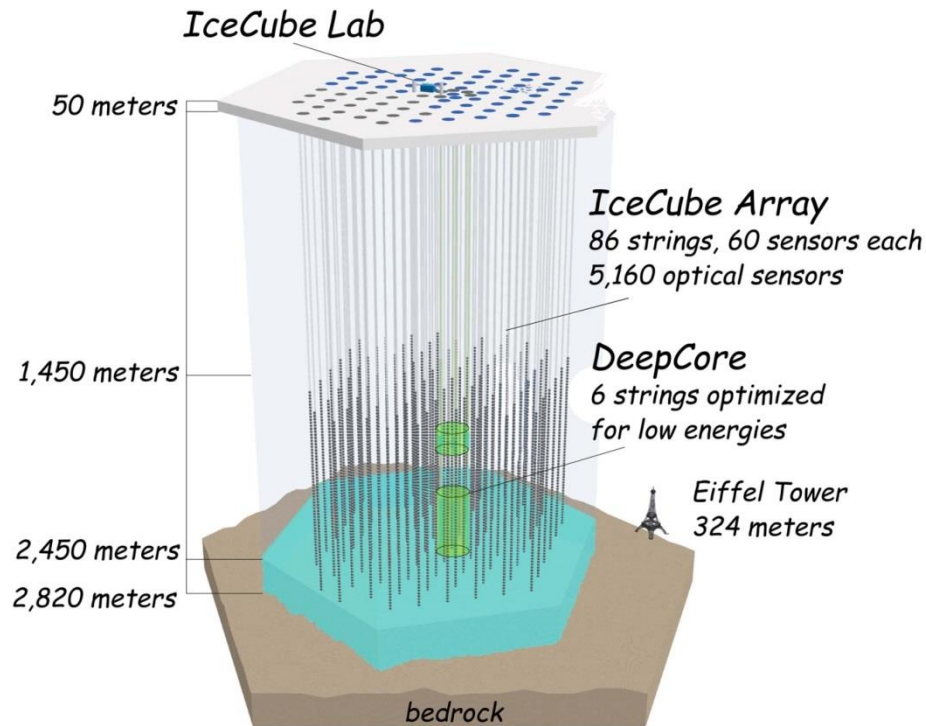
But, it might be extended to explain mysteries in our universe...

- Neutrino mass
- Inflation
- Baryon asymmetry
- Dark matter
- **IceCube??**

We try to explain all of them!

# IceCube experiment

IceCube is located at the south pole. Its volume is around  $1\text{km}^3$ .

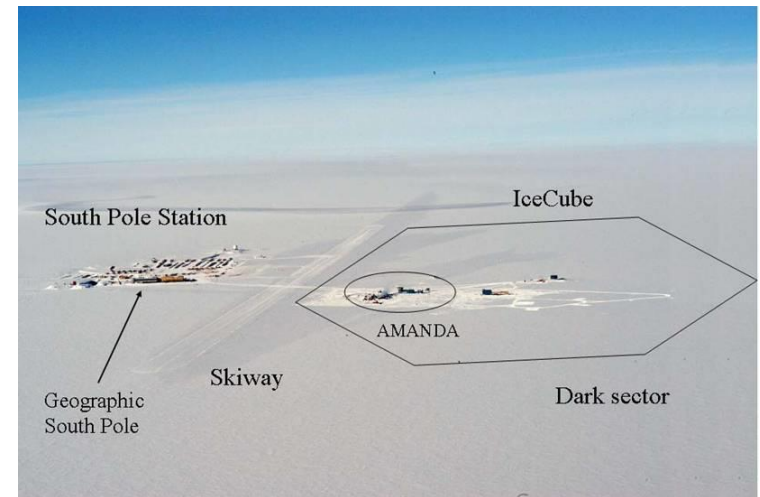
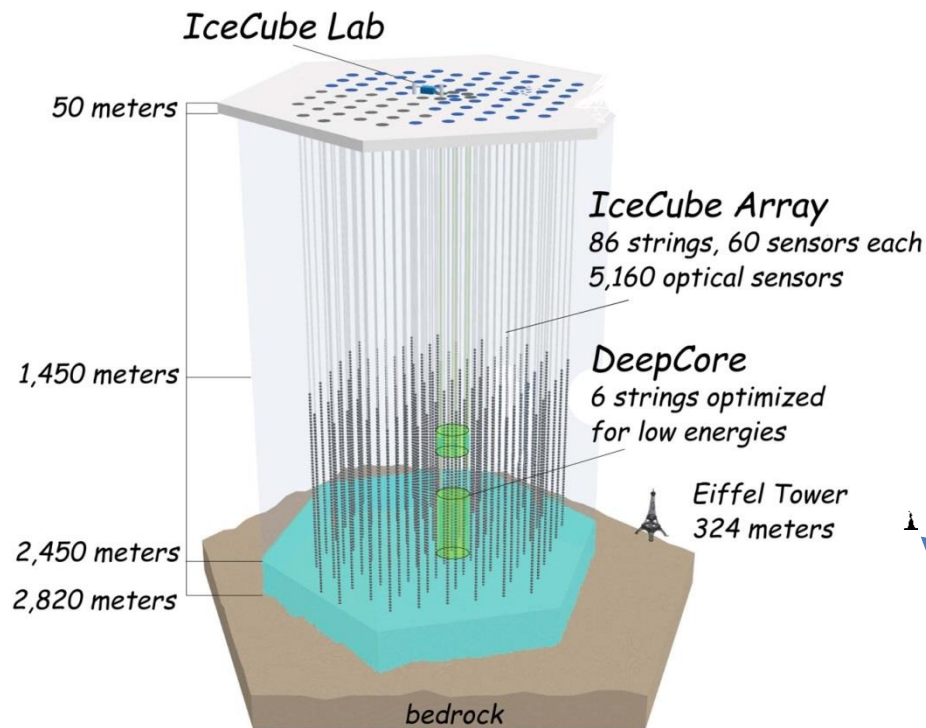


[ <http://www.icecube.umd.edu/~goodman/IceCube.htm> ]

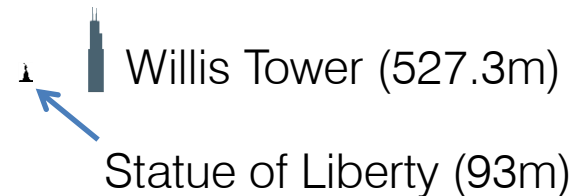
[<http://newscenter.lbl.gov/2010/12/17/completing-icecube/>]

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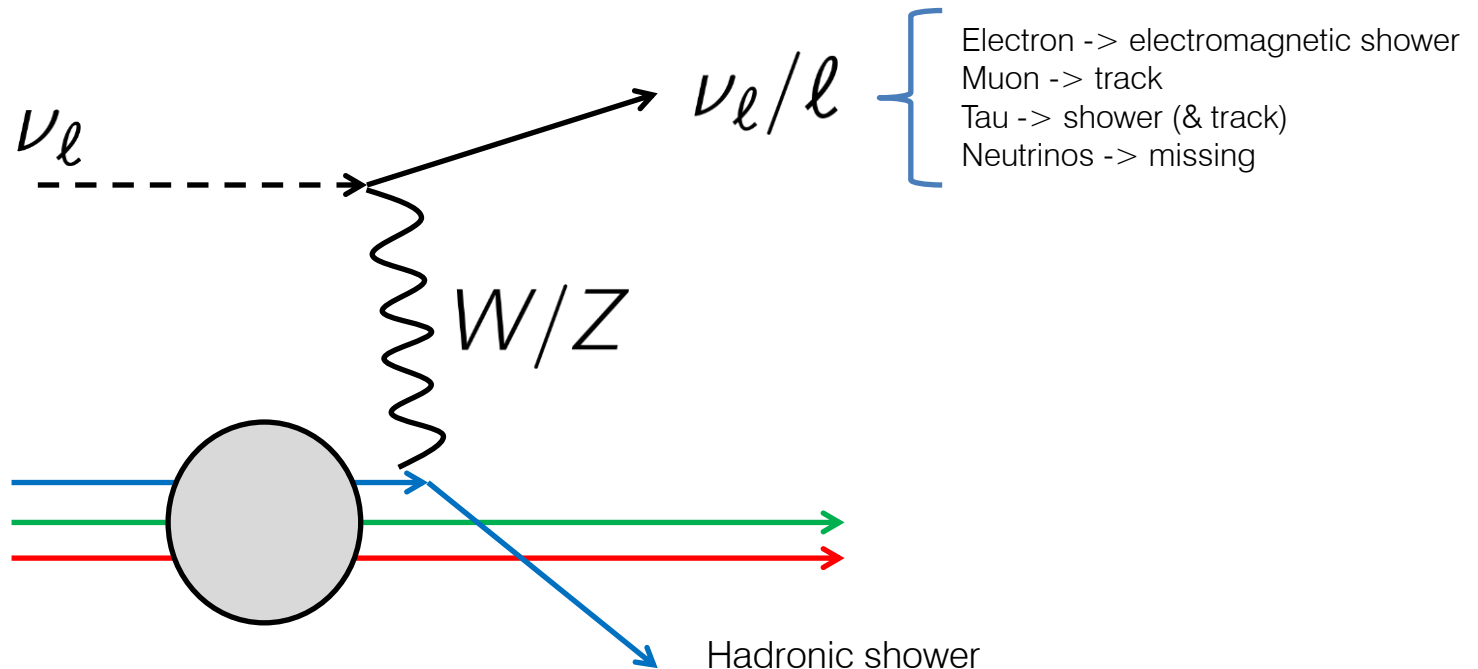
[ <http://www.icecube.umd.edu/~goodman/IceCube.htm> ]



[<http://newscenter.lbl.gov/2010/12/17/completing-icecube/>]

# Detection principle

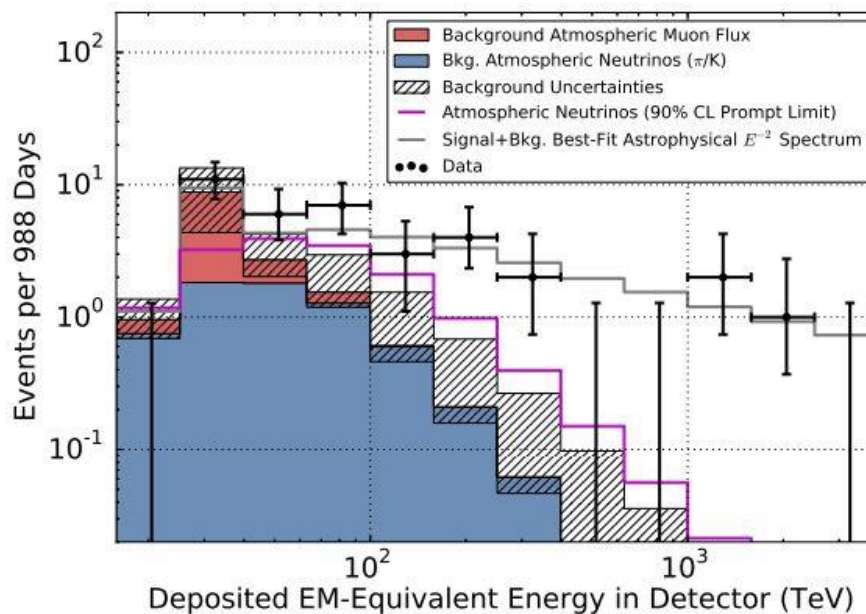
Incoming neutrino hits material by **Neutral Current / Charged Current interaction**.



Electromagnetic / hadronic shower creates a lot of energetic particles.  
Energetic charged particles emit **Cherenkov light**.

# 3 years observation

**5.7 sigma** deviation from Atmospheric neutrino background!  
Origin of high energy neutrino is **extraterrestrial**.

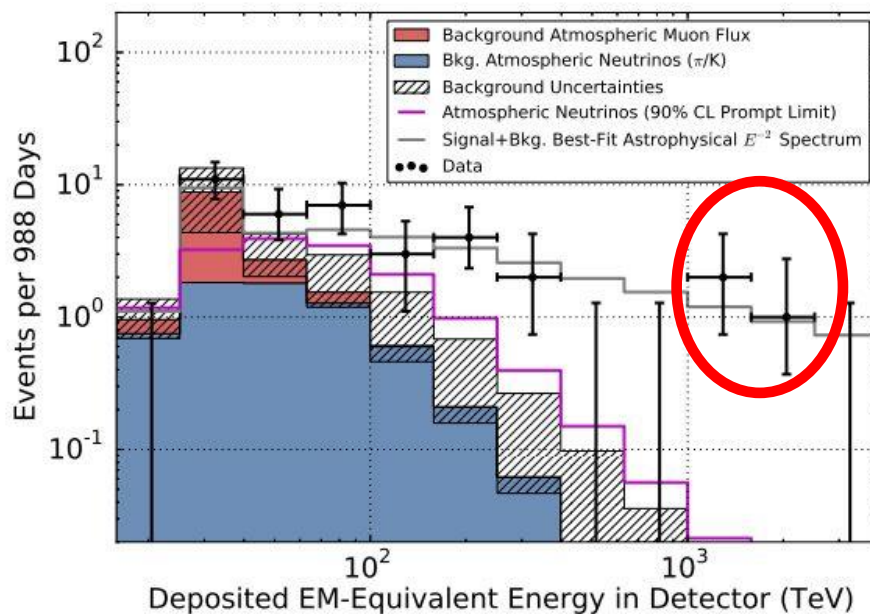


[IceCube Collaboration, arXiv:1405.5303]

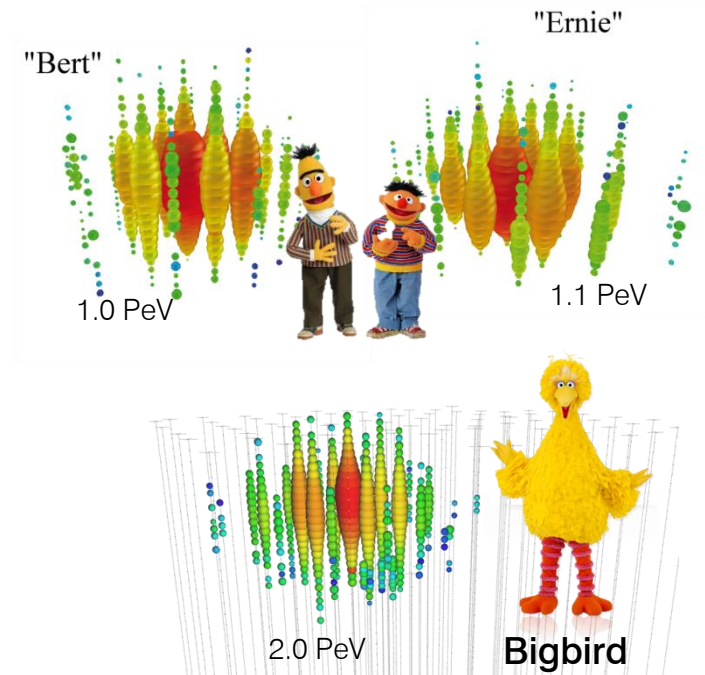
Darkmatter???

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**5.7 sigma** deviation from Atmospheric neutrino background!  
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[IceCube Collaboration, arXiv:1405.5303]



Darkmatter???

# Outline

## 1. Model

- Yukawa couplings for right-handed neutrinos
- Neutrino masses

## 2. Inflation and reheating

- Inflation
- Non-thermal leptogenesis
- Non-thermal dark matter production

## 3. PeV neutrino from decaying dark matter

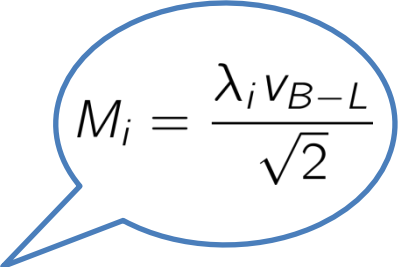
- High energy neutrino events at the IceCube experiment

# 1. Model

# Our model

Standard model

- + 3 right-handed neutrinos w/ Majorana masses
- + U(1)<sub>B-L</sub> gauge symmetry & B-L Higgs boson


$$M_i = \frac{\lambda_i v_{B-L}}{\sqrt{2}}$$

$$\mathcal{L} = \mathcal{L}_{SM} - \left( y_{\nu}^{ij} H N_i \ell_j + \frac{\lambda_i}{2} \phi_{B-L} N_i^2 + h.c. \right) - \kappa \left( |\phi_{B-L}|^2 - \frac{v_{B-L}^2}{2} \right)^2$$

We assume  $y_{1i}$ 's are **extremely small but non-zero**.

- Suppressed by  $Z_2$  parity : ( $N_1 \rightarrow -N_1$ )

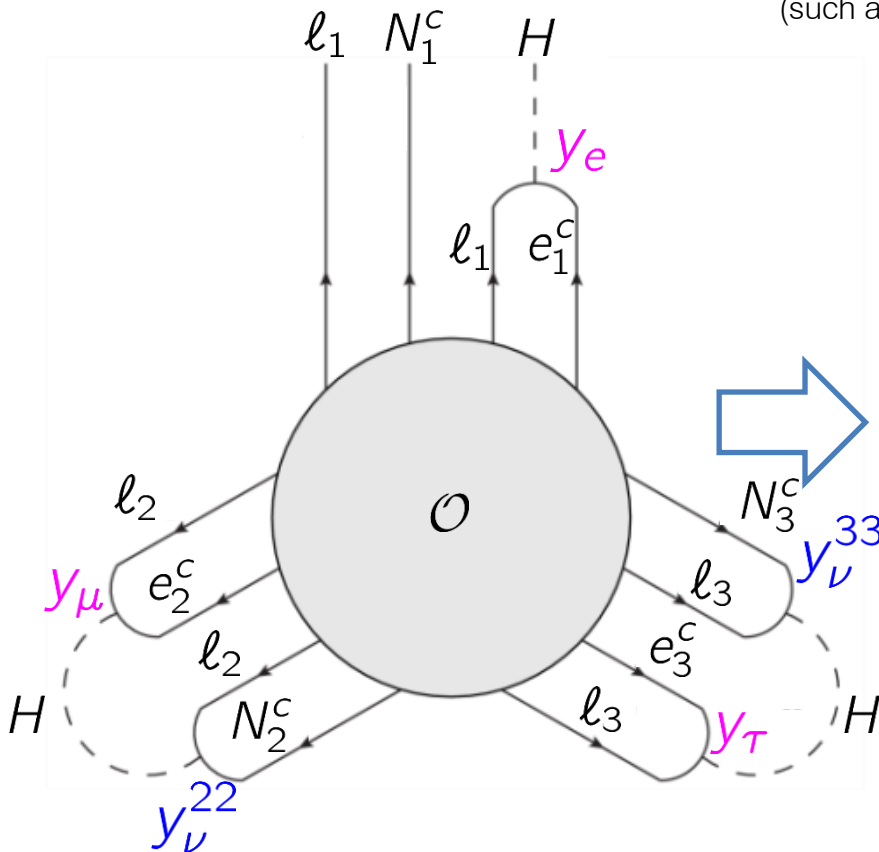
$$y_{\nu} = \begin{pmatrix} \ll 1 & \ll 1 & \ll 1 \\ y_{\nu}^{21} & y_{\nu}^{22} & y_{\nu}^{23} \\ y_{\nu}^{31} & y_{\nu}^{32} & y_{\nu}^{33} \end{pmatrix}$$

- $N_1$  can be a candidate of **decaying darkmatter**.

# Why small but non-zero $y_{1i}$ ?

We assume that  $Z_2$  parity ( $N_1 \rightarrow -N_1$ ) is **conserved classically**,  
but **violated by some quantum effect**.

e.g., we can write,  $\mathcal{O} \sim \frac{1}{\Lambda^{14}} (\ell_1 \ell_2) (\ell_2 \ell_3) (\ell_3 \ell_1) e_1^c e_2^c e_3^c N_1^c N_2^c N_3^c$   
(such a operator may be generated by some non-perturbative effect.)



$$y_\nu^{1k} \sim (\text{very small number}) \\ \times (\det y_e) \epsilon^{ijk} y_\nu^{2i} y_\nu^{3j}$$

Normal hierarchy  $\rightarrow y_\nu^{1k} \propto U_{k1}$   
 $|y_\nu^{1e}|^2 : |y_\nu^{1\mu}|^2 : |y_\nu^{1\tau}|^2 \simeq 0.7 : 0.2 : 0.1$

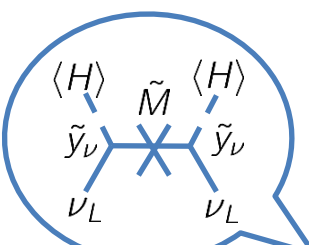
Inverted hierarchy  $\rightarrow y_\nu^{1k} \propto U_{k3}$   
 $|y_\nu^{1e}|^2 : |y_\nu^{1\mu}|^2 : |y_\nu^{1\tau}|^2 \simeq 0.02 : 0.38 : 0.6$

# Neutrino masses

Neutrino mass is generated by **seesaw mechanism**.

RH neutrino sector in our model is essentially **two RH neutrino model**.

[ Frampton, Glashow, Yanagida (2002) ]



$$y_\nu = \begin{pmatrix} \sim 0 & \sim 0 & \sim 0 \\ y_\nu^{21} & y_\nu^{22} & y_\nu^{23} \\ y_\nu^{31} & y_\nu^{32} & y_\nu^{33} \end{pmatrix} \tilde{y}_\nu$$

$$M = \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \tilde{M}$$

Neutrino mass matrix:

$$m_\nu = \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix} = (U^T \tilde{y}_\nu^T \tilde{M}^{-1} \tilde{y}_\nu U) \langle H \rangle^2 \longrightarrow \begin{array}{l} \text{Rank 2 matrix} \\ \text{Lightest neutrino is massless.} \end{array}$$

(U : Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix )

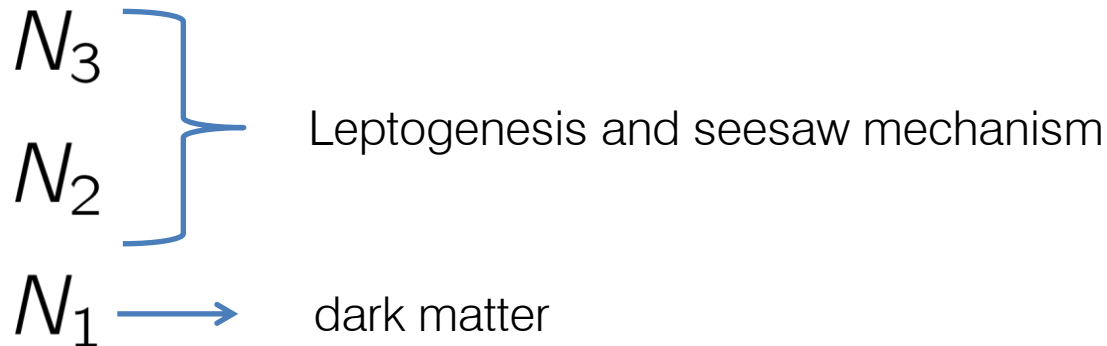
$$\Delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2, \quad \Delta m_{31}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2 \quad [\text{Particle Data Group}]$$

- a) Normal hierarchy  $\xrightarrow{m_1 < m_2 < m_3}$   $m_1 = 0 \text{ eV}, \quad m_2 \simeq 0.0087 \text{ eV}, \quad m_3 \simeq 0.048 \text{ eV}$
- b) Inverted hierarchy  $\xrightarrow{m_3 < m_1 < m_2}$   $m_1 \simeq 0.048 \text{ eV}, \quad m_2 \simeq 0.049 \text{ eV}, \quad m_3 = 0 \text{ eV}$

## 2. Inflation and reheating

# Thermal history

- Inflation ( driven by B-L Higgs boson)
- Reheating ( B-L Higgs boson to RH neutrinos )
  - Leptogenesis (decay of 2<sup>nd</sup> lightest RH neutrino)
  - Non-thermal Dark matter production (lightest RH neutrino)

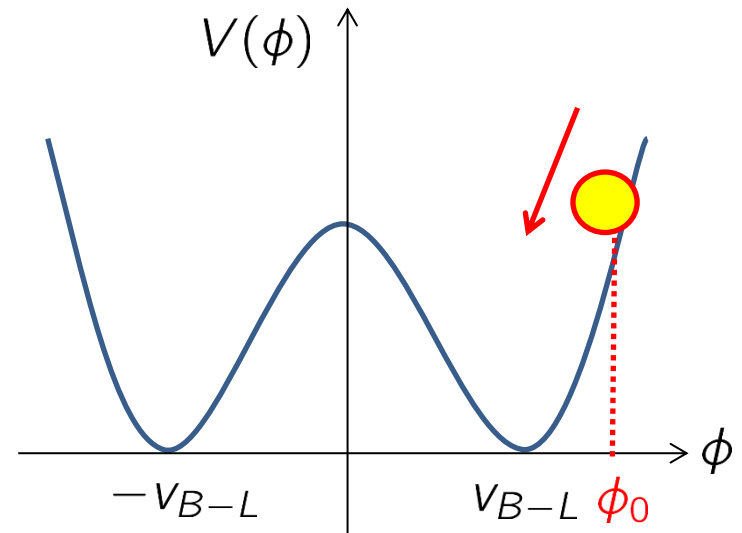
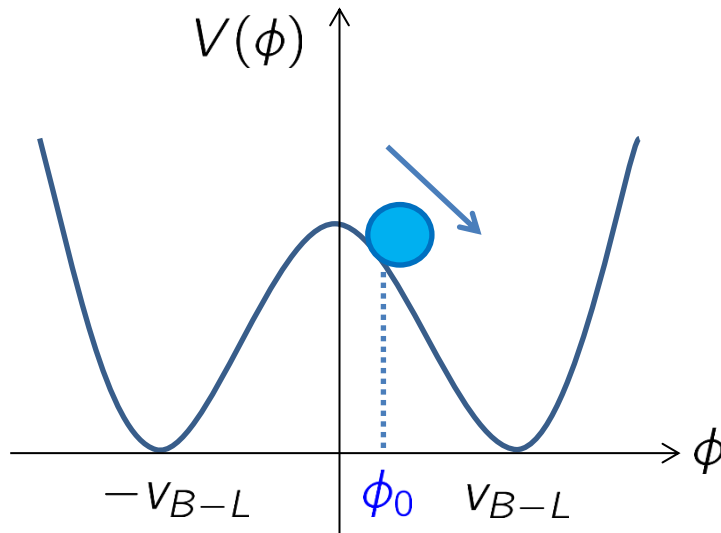


# Inflation by B-L Higgs boson

$$V(\phi) = \frac{\kappa}{4} (\phi^2 - v_{B-L}^2)^2 \quad \left( \phi_{B-L} = \frac{1}{\sqrt{2}} (\phi + iG) \right) \quad [ \text{Okada, Shafi (2013)} ]$$

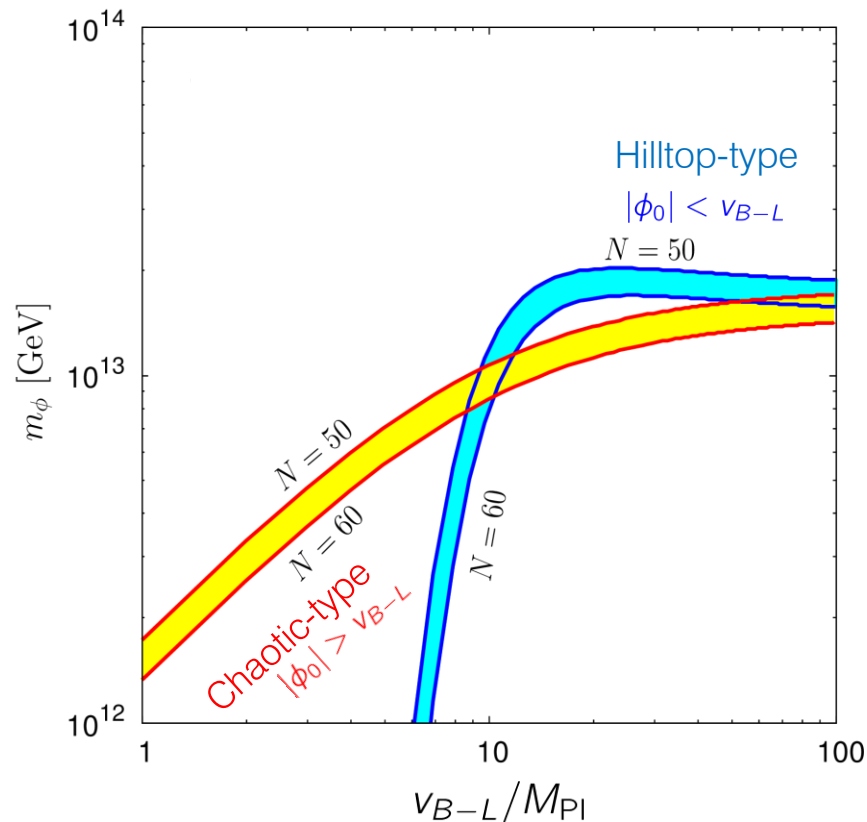
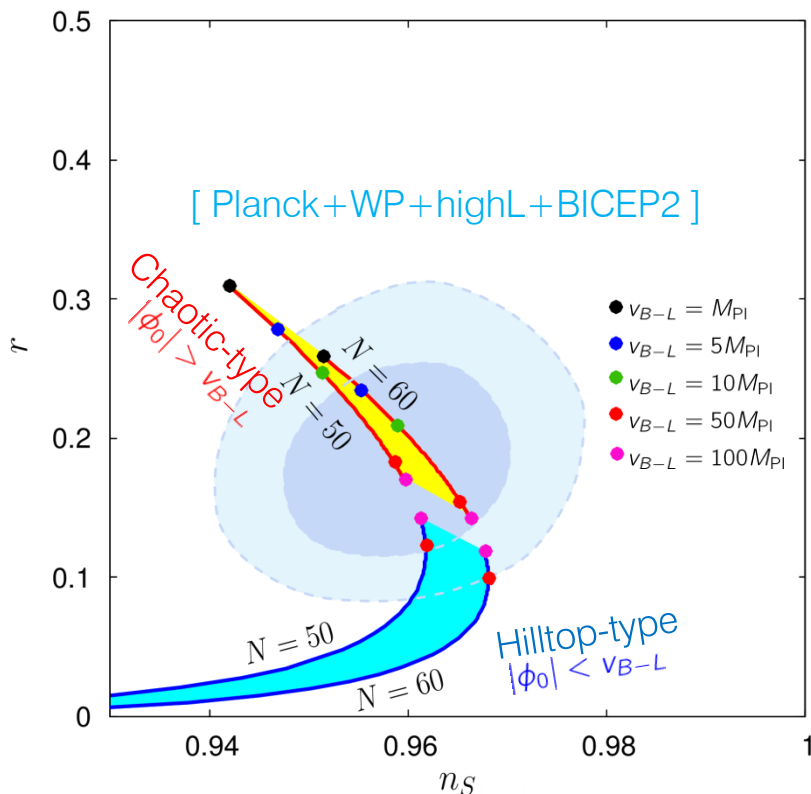
We have two choices for initial condition.

- Hilltop-type
- Chaotic-type



# Inflation with BICEP2

$$V(\phi) = \frac{\kappa}{4} (\phi^2 - v_{B-L}^2)^2$$



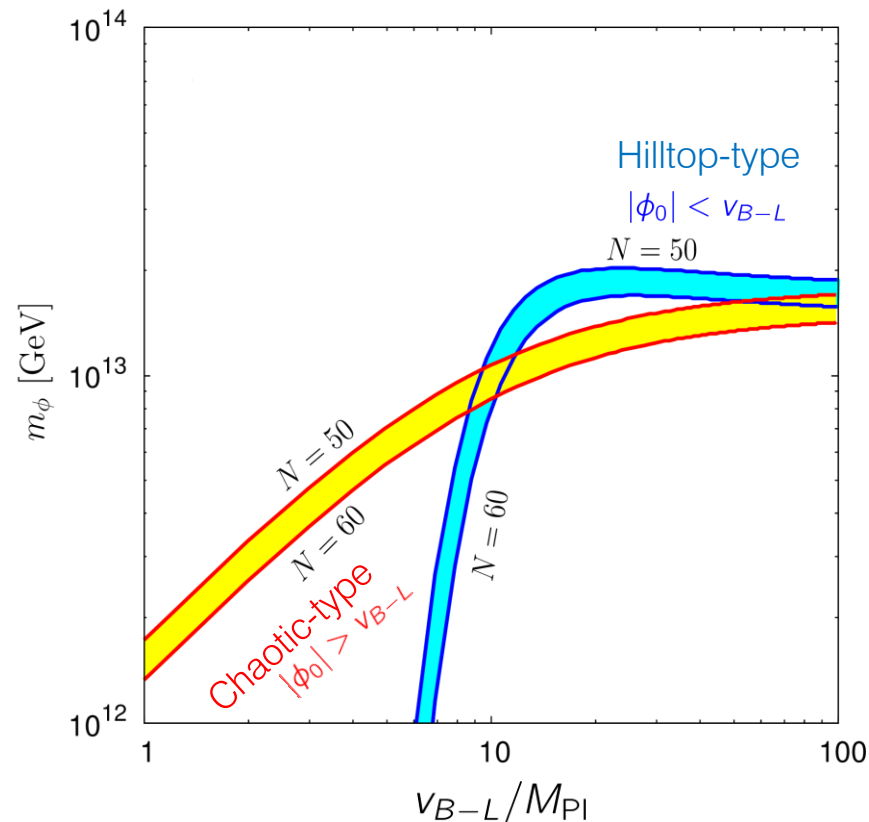
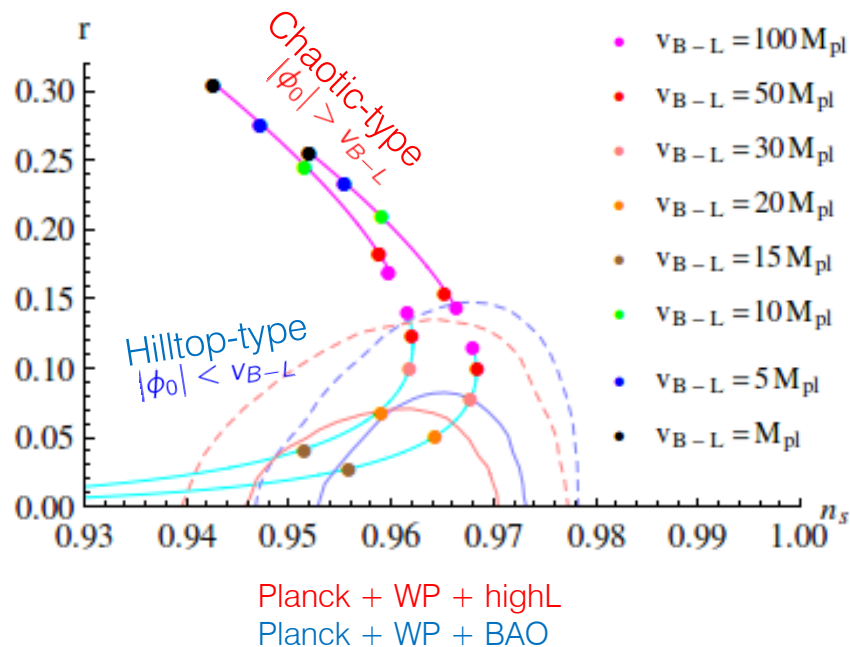
CMB observation suggests  $m_\phi \sim 10^{13}$  GeV

Chaotic type initial condition with  $v_{B-L} / M_{Pl} > 5$  is consistent with BICEP2 data.

[Higaki, Kitano, RS (2014)]

# Inflation without BICEP2

$$V(\phi) = \frac{\kappa}{4} (\phi^2 - v_{B-L}^2)^2$$



CMB observation suggests  $m_\phi \sim 10^{13}$  GeV

Hilltop type initial condition with  $v_{B-L} / M_{Pl} = 15-30$  is consistent with Planck data.

[Higaki, Kitano, RS (2014)]

# Reheating and decay products

Inflaton decays into RH neutrinos :  $\phi \rightarrow N_i N_i$

$$\mathcal{L} \ni -\frac{M_i}{2v_{B-L}}\phi N_i N_i$$

- Number of  $\phi$  per entropy at the time of reheating

$$\frac{n_\phi}{s} = \frac{\rho_\phi/m_\phi}{s} = \frac{3}{4} \frac{T_R}{m_\phi}$$

$T_R$  is reheating temperature,  
which is determined from  $H(T_R) = \Gamma_\phi$

$H$  : Hubble expansion rate

$\Gamma_\phi$  : decay width of inflaton

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- Number density of decay products

$$\frac{n_{N_1}}{s} \simeq \frac{3}{4} \frac{T_R}{m_\phi} \times 2 \times \text{Br}(\phi \rightarrow N_1 N_1)$$

$$\frac{n_{N_2}}{s} \simeq \frac{3}{4} \frac{T_R}{m_\phi} \times 2 \times \text{Br}(\phi \rightarrow N_2 N_2)$$



$$\frac{n_B}{s} \simeq \frac{n_{N_2}}{s} \times \frac{\Gamma(N_2 \rightarrow \ell H) - \Gamma(N_2 \rightarrow \bar{\ell} H^\dagger)}{\Gamma(N_2 \rightarrow \ell H) + \Gamma(N_2 \rightarrow \bar{\ell} H^\dagger)} \times \left(-\frac{28}{79}\right)$$

# Numerical results

We assume  $M_1 \ll M_2 < m_\phi < M_3$   $\begin{cases} \text{Br}(\phi \rightarrow N_1 N_1) & \simeq M_1^2/M_2^2 \\ \text{Br}(\phi \rightarrow N_2 N_2) & \simeq 1 \end{cases}$

$$\left\{ \begin{array}{l} T_R \simeq 2 \times 10^7 \text{ GeV} \left( \frac{M_2}{10^{12} \text{ GeV}} \right) \left( \frac{m_\phi}{10^{13} \text{ GeV}} \right)^{1/2} \left( \frac{v_{B-L}}{5M_{\text{Pl}}} \right)^{-1} \\ \Omega_{N_1} \simeq 0.2 \left( \frac{M_1}{4 \text{ PeV}} \right)^3 \left( \frac{M_2}{10^{12} \text{ GeV}} \right)^{-1} \left( \frac{m_\phi}{10^{13} \text{ GeV}} \right)^{-1/2} \left( \frac{v_{B-L}}{5M_{\text{Pl}}} \right)^{-1} \\ \left. \frac{n_B}{s} \right|_{\text{max}} \simeq \left( \frac{M_2}{10^{12} \text{ GeV}} \right)^2 \left( \frac{m_\phi}{10^{13} \text{ GeV}} \right)^{-1/2} \left( \frac{v_{B-L}}{5M_{\text{Pl}}} \right)^{-1} \times \begin{cases} 1 \times 10^{-10} & \text{(Normal hierarchy)} \\ 2 \times 10^{-12} & \text{(Inverted hierarchy)} \end{cases} \end{array} \right.$$

(Upper bound on  $e$  depends on mass hierarchy)

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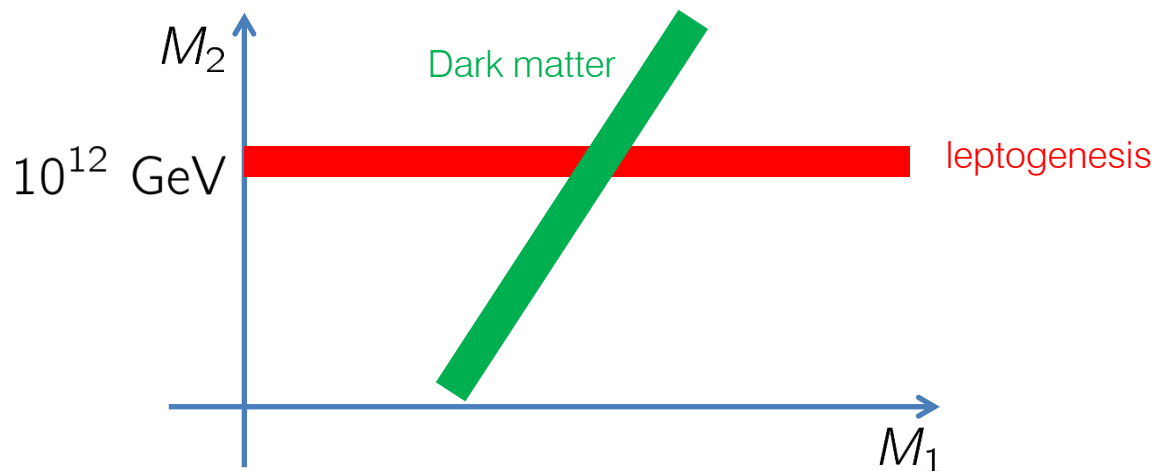


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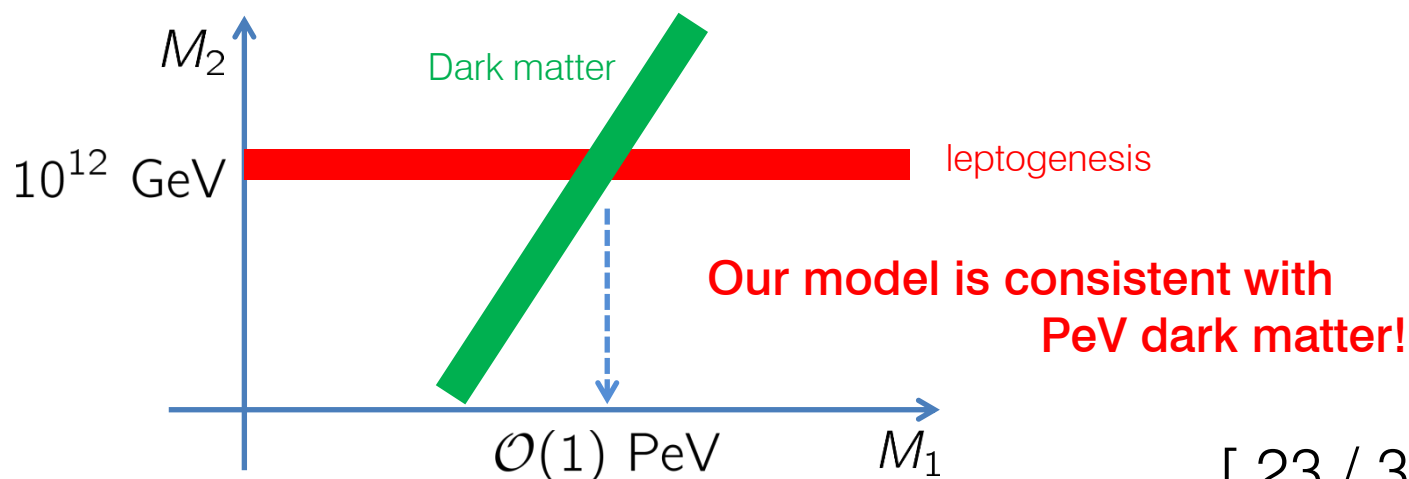


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### 3. PeV neutrinos from dark matter

# Decay of dark matter

$$\mathcal{L} \ni -y_{\nu,1j} H N_1 \ell_j - \frac{M_1}{2} N_1^2$$

- Lifetime

$$\tau_{N_1} \sim 10^{29} \text{ s} \left( \frac{M_1}{1 \text{ PeV}} \right) \left( \frac{\sqrt{\sum_i |y_{1i}|^2}}{10^{-29}} \right)^{-2}$$

- Decay modes and branching fractions

$$e^\pm W^\mp \quad \nu_e Z, \bar{\nu}_e Z \quad \nu_e h, \bar{\nu}_e h$$

$$\mu^\pm W^\mp \quad \nu_\mu Z, \bar{\nu}_\mu Z \quad \nu_\mu h, \bar{\nu}_\mu h$$

$$\tau^\pm W^\mp \quad \nu_\tau Z, \bar{\nu}_\tau Z \quad \nu_\tau h, \bar{\nu}_\tau h$$

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$e^\pm W^\mp$	$\nu_e Z, \bar{\nu}_e Z$	$\nu_e h, \bar{\nu}_e h$
$\mu^\pm W^\mp$	$\nu_\mu Z, \bar{\nu}_\mu Z$	$\nu_\mu h, \bar{\nu}_\mu h$
$\tau^\pm W^\mp$	$\nu_\tau Z, \bar{\nu}_\tau Z$	$\nu_\tau h, \bar{\nu}_\tau h$
<b>0.50</b>	<b>0.25</b>	<b>0.25</b>

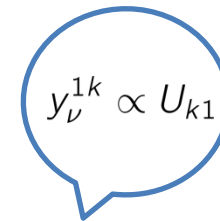
c.f.) goldstone boson equivalence theorem

# Decay of dark matter

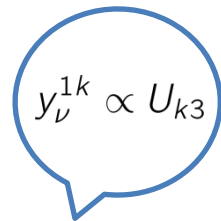
$$\mathcal{L} \ni -y_{\nu,1j} H N_1 \ell_j - \frac{M_1}{2} N_1^2$$

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Normal  
hierarchy



Inverted  
hierarchy

- Decay modes and branching fractions

$e^\pm W^\mp$	$\nu_e Z, \bar{\nu}_e Z$	$\nu_e h, \bar{\nu}_e h$	<b>0.68</b>	<b>0.02</b>
$\mu^\pm W^\mp$	$\nu_\mu Z, \bar{\nu}_\mu Z$	$\nu_\mu h, \bar{\nu}_\mu h$	<b>0.24+0.02 cosδ</b>	<b>0.38</b>
$\tau^\pm W^\mp$	$\nu_\tau Z, \bar{\nu}_\tau Z$	$\nu_\tau h, \bar{\nu}_\tau h$	<b>0.08-0.02 cosδ</b>	<b>0.60</b>

# Neutrino energy flux at the decay time

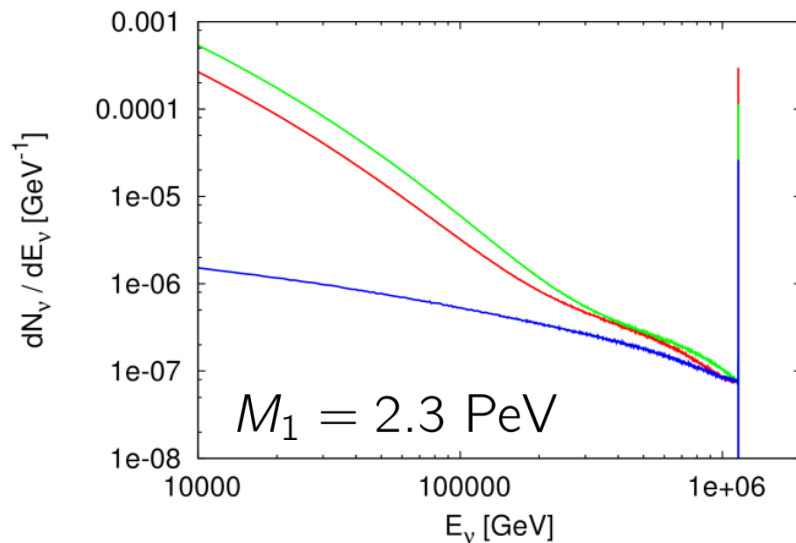
Energy spectrum at the decay time

$\nu_e + \bar{\nu}_e$

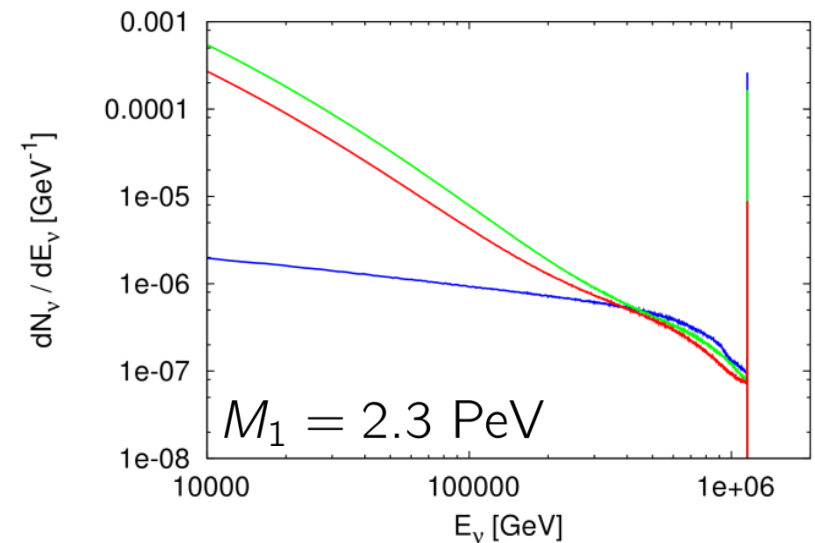
$\nu_\mu + \bar{\nu}_\mu$

$\nu_\tau + \bar{\nu}_\tau$

Normal hierarchy



Inverted hierarchy



[Higaki, Kitano, RS (2014)]  
(simulated by PYTHIA 8.1)

# Calculation of number of events

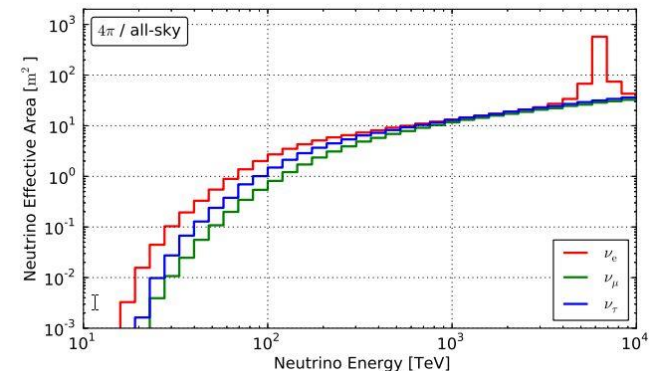
- Neutrino flux at the earth

$$\frac{d\Phi}{dE} = \int d\Omega \int dr \frac{1}{4\pi} \times \overset{\text{Number density of DM}}{\frac{\rho(r, \theta, \phi)}{M_N}} \times \overset{\text{Number of neutrino per energy per time}}{\frac{1}{\tau_N} \frac{dN}{dE}} \quad \left\{ \begin{array}{l} \bullet \text{ Contribution from our galaxy} \\ \bullet \text{ Extra galactic contribution} \end{array} \right.$$

- Number of expected observed event at the IceCube

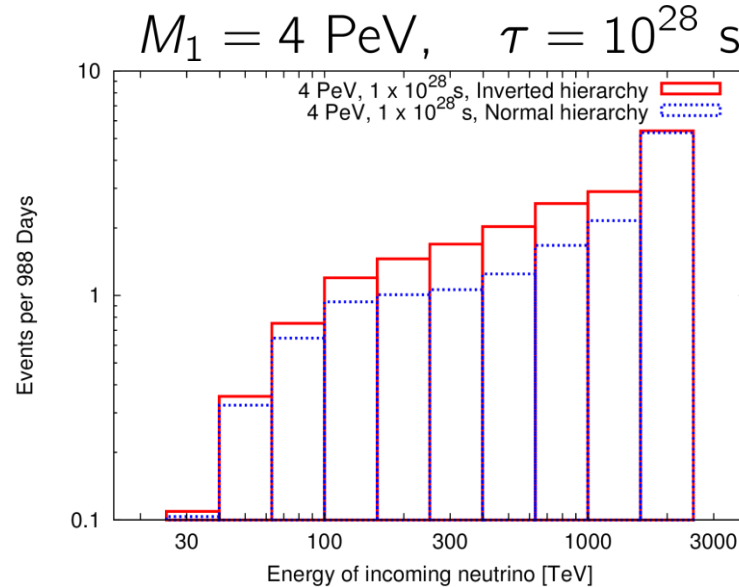
$$N_{\text{obs}} = 988 \text{days} \times \int dE \left( \sigma_{\text{eff}}(E) \frac{d\Phi}{dE} \right)$$

$\sigma_{\text{eff}}$  is effective area for neutrino energy E.



[ IceCube collaboration arxiv:1311.5238 ]

# Number of events



[Higaki, Kitano, RS (2014)]

For Normal hierarchy,

$$N(1 \text{ PeV} \leq E_\nu) = 5.0 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 3.0 \times \left( \frac{\tau_{N_1}}{1.6 \times 10^{28} \text{ s}} \right)$$

For Inverted hierarchy,

$$N(1 \text{ PeV} \leq E_\nu) = 5.6 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 3.0 \times \left( \frac{\tau_{N_1}}{1.9 \times 10^{28} \text{ s}} \right)$$

PeV dark matter with its lifetime to be around  $10^{28} \text{ s}$   
can explain the event excess at the IceCube experiment.

# Summary

We consider **a simple extension** of the SM:

- Three right-handed neutrinos ( $N_1, N_2, N_3$ )
- B-L gauge symmetry and B-L Higgs boson ( $\phi_{B-L}$ )
- Approximate  $Z_2$  parity for  $N_1$

Our model explains,

- |                    |   |                                     |
|--------------------|---|-------------------------------------|
| • Inflation        | → | Driven by B-L Higgs boson           |
| • Dark matter      | → | $N_1$ with $M_1 \sim O(\text{PeV})$ |
| • Baryon asymmetry | → | Leptogenesis from $N_2$ decay       |
| • Neutrino mass    | → | Seesaw from $N_2$ and $N_3$         |
| • IceCube excess   | → | Decay of $N_1$                      |



A. Backup slides

# Flavor structure of $y_{1i}$ (Normal hierarchy)

- Ibarra-Casas parametrization

$$m_\nu = (\underbrace{U^T}_{\text{PMNS matrix}} \tilde{y}_\nu^T \tilde{M}^{-1} \tilde{y}_\nu \underbrace{U}_{\text{PMNS matrix}}) \langle H \rangle^2 \quad \longleftrightarrow \quad \begin{aligned} \tilde{y}_\nu &= \frac{1}{\langle H \rangle} \tilde{M}^{1/2} R m_\nu^{1/2} U^\dagger \\ R &= \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix} \end{aligned}$$

$z$  : a complex parameter



$$\begin{aligned} y_\nu^{2i} &= \frac{\sqrt{M_2}}{\langle H \rangle} (\sqrt{m_2} U_{i2}^* \cos z - \sqrt{m_3} U_{i3}^* \sin z), \\ y_\nu^{3i} &= \frac{\sqrt{M_3}}{\langle H \rangle} (\sqrt{m_2} U_{i2}^* \sin z + \sqrt{m_3} U_{i3}^* \cos z) \end{aligned}$$



$$\begin{aligned} y_\nu^{1k} &= c \epsilon^{ijk} y_\nu^{2i} y_\nu^{3j} \\ &= \frac{c \sqrt{M_2 M_3 m_2 m_3}}{\langle H \rangle^2} \times U_{k1} \end{aligned}$$

**Flavor structure of  $y_{1k}$  is determined by PMNS matrix and mass hierarchy.**

# Flavor structure of $y_{1i}$ (Inverted hierarchy)

- Ibarra-Casas parametrization

$$m_\nu = (\underbrace{U^T}_{\text{PMNS matrix}} \tilde{y}_\nu^T \tilde{M}^{-1} \tilde{y}_\nu \underbrace{U}_{\text{PMNS matrix}}) \langle H \rangle^2 \quad \longleftrightarrow \quad \tilde{y}_\nu = \frac{1}{\langle H \rangle} \tilde{M}^{1/2} R m_\nu^{1/2} U^\dagger$$

$$R = \begin{pmatrix} \cos z & \sin z & 0 \\ -\sin z & \cos z & 0 \end{pmatrix}$$

$z$  : a complex parameter



$$y_\nu^{2i} = \frac{\sqrt{M_2}}{\langle H \rangle} (\sqrt{m_1} U_{i1}^* \cos z - \sqrt{m_2} U_{i2}^* \sin z),$$

$$y_\nu^{3i} = \frac{\sqrt{M_3}}{\langle H \rangle} (\sqrt{m_1} U_{i1}^* \sin z + \sqrt{m_2} U_{i2}^* \cos z)$$



$$y_\nu^{1k} = c \epsilon^{ijk} y_\nu^{2i} y_\nu^{3j}$$

$$= \frac{c \sqrt{M_2 M_3 m_1 m_2}}{\langle H \rangle^2} \times U_{k3}$$

**Flavor structure of  $y_{1k}$  is determined by PMNS matrix and mass hierarchy.**

# Upper bound on $\epsilon$

$$y_{1i} \simeq 0, \quad M_2 \ll M_3$$

$$\epsilon = \frac{\Gamma(N_2 \rightarrow \ell H) - \Gamma(N_2 \rightarrow \bar{\ell} H^\dagger)}{\Gamma(N_2 \rightarrow \ell H) + \Gamma(N_2 \rightarrow \bar{\ell} H^\dagger)} \simeq -\frac{3}{16\pi} \frac{\text{Im}(y_\nu y_\nu^\dagger)_{23}^2}{(y_\nu y_\nu^\dagger)_{22}} \frac{M_2}{M_3}$$

[ Covi, Roulet, Vissani (1996) ]



- Normal hierarchy

$$\epsilon \simeq -\frac{3}{16\pi} \frac{M_2}{v^2} \frac{\text{Im}[m_2^2 \cos^2 z + m_3^2 \sin^2 z]}{m_2 |\cos z|^2 + m_3 |\sin z|^2}$$

$$\Rightarrow |\epsilon| < \frac{3M_2}{16\pi v^2} (m_3 - m_2)$$

- Inverted hierarchy

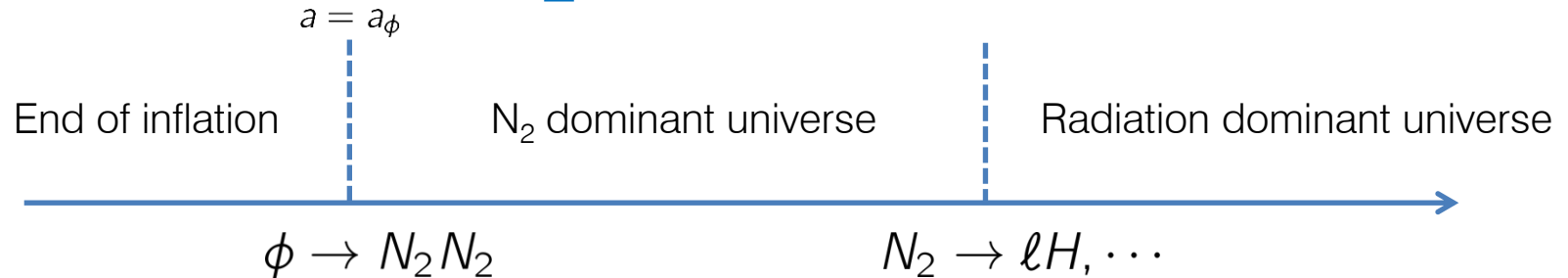
$$\epsilon \simeq -\frac{3}{16\pi} \frac{M_2}{v^2} \frac{\text{Im}[m_1^2 \cos^2 z + m_2^2 \sin^2 z]}{m_1 |\cos z|^2 + m_2 |\sin z|^2}$$

$$\Rightarrow |\epsilon| < \frac{3M_2}{16\pi v^2} (m_2 - m_1)$$

[ Harigaya, Ibe, Yanagida (2012) ]

(z : a complex parameter)

# Decay time of $N_2$



For  $N_2$  dominant era,

$$H = \Gamma_\phi \left( \frac{a}{a_\phi} \right)^{-2} \xrightarrow{a_{\text{nonrela}}/a_\phi \sim m_\phi/M_2} t_{\text{nonrela}}^{-1} \sim \Gamma_\phi \left( \frac{m_\phi}{M_2} \right)^{-2}$$

The time when  $N_2$  becomes non-relativistic.

a)  $t_{\text{nonrela}} > \Gamma_2^{-1}$  :  $N_2$  decays when  $N_2$  is relativistic.

$$\frac{n_{N_2}}{s} \sim \frac{T_\phi}{m_\phi}$$

b)  $t_{\text{nonrela}} < \Gamma_2^{-1}$  :  $N_2$  decays when  $N_2$  is non-relativistic.

$$\frac{n_{N_2}}{s} \sim \frac{T_2}{M_2} \sim \frac{T_\phi}{m_\phi} \Delta$$

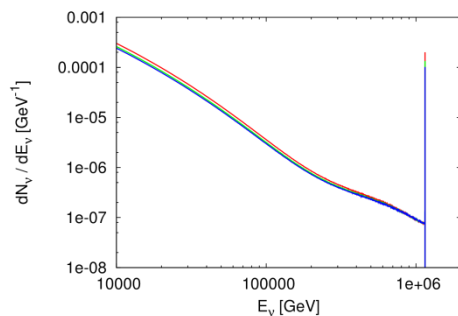
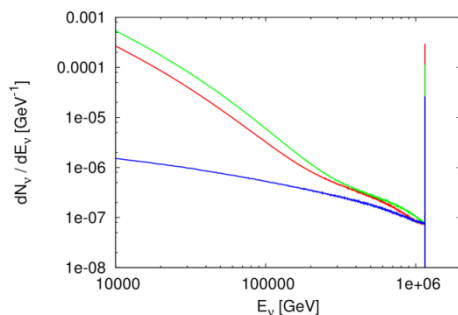
$$\Delta = \Gamma_2 t_{\text{nonrela}} = \frac{\Gamma_2}{\Gamma_\phi} \frac{m_\phi^2}{M_2^2} < 1$$

Everything is diluted by entropy production!

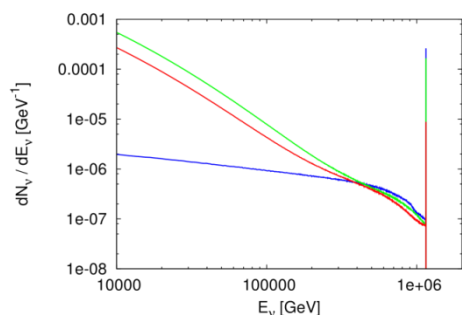
# Effect of neutrino oscillation

Energy spectrum at the decay time (simulated by PYTHIA 8.1)

Normal hierarchy



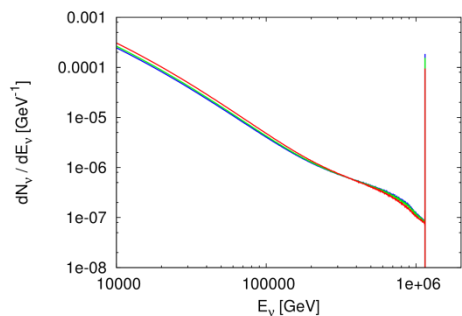
Inverted hierarchy



$\nu_e + \bar{\nu}_e$

$\nu_\mu + \bar{\nu}_\mu$

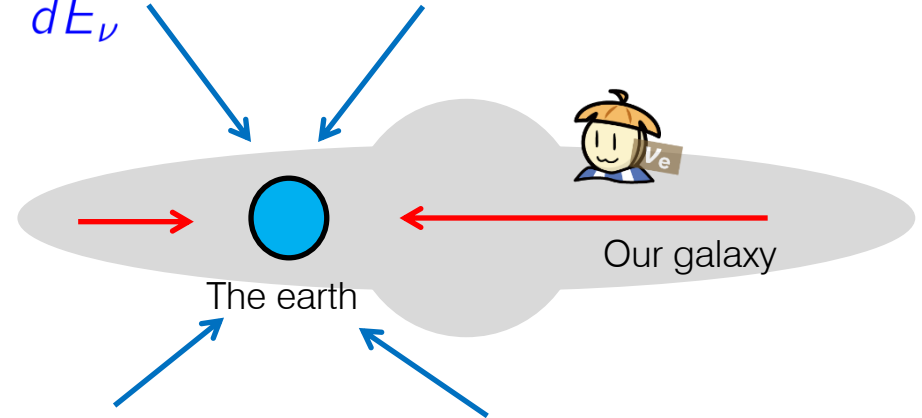
$\nu_\tau + \bar{\nu}_\tau$



$$P(\nu_\ell \rightarrow \nu_{\ell'}) \simeq \begin{pmatrix} 0.5 & 0.3 & 0.2 \\ 0.3 & 0.3 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix}$$

# Neutrino energy flux at the Earth

$$\text{Neutrino flux at the Earth} = \frac{d\Phi_{\text{halo}}}{dE_\nu} + \frac{d\Phi_{\text{eg}}}{dE_\nu}$$



- Contribution from our galaxy

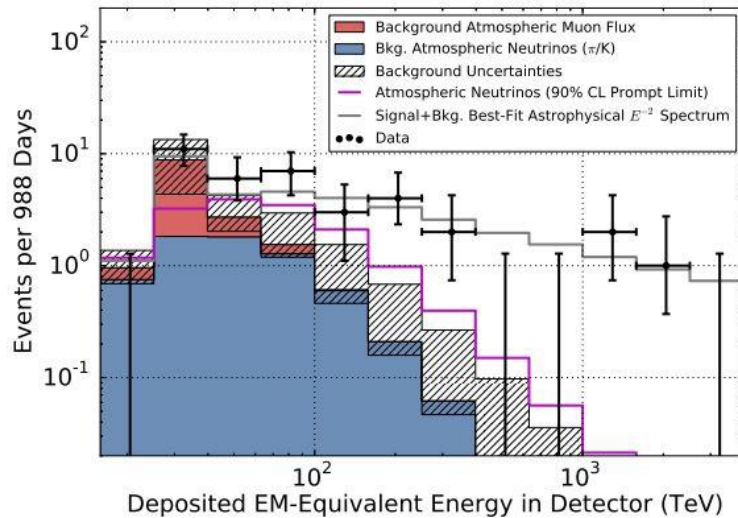
$$\frac{d\Phi_{\text{halo}}}{dE_\nu} = D_{\text{halo}} \frac{dN_\nu}{dE_\nu}$$

$$\left\{ \begin{array}{l} D_{\text{halo}} = \frac{1}{4\pi} \int_{-1}^1 d \sin \theta \int_0^{2\pi} \left( \frac{1}{4\pi M_1 \tau_{N_1}} \int_0^\infty ds \rho_{\text{halo}}(r(s, \theta, \phi)) \right) \\ r(s, \theta, \phi) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos \theta \cos \phi} \end{array} \right.$$

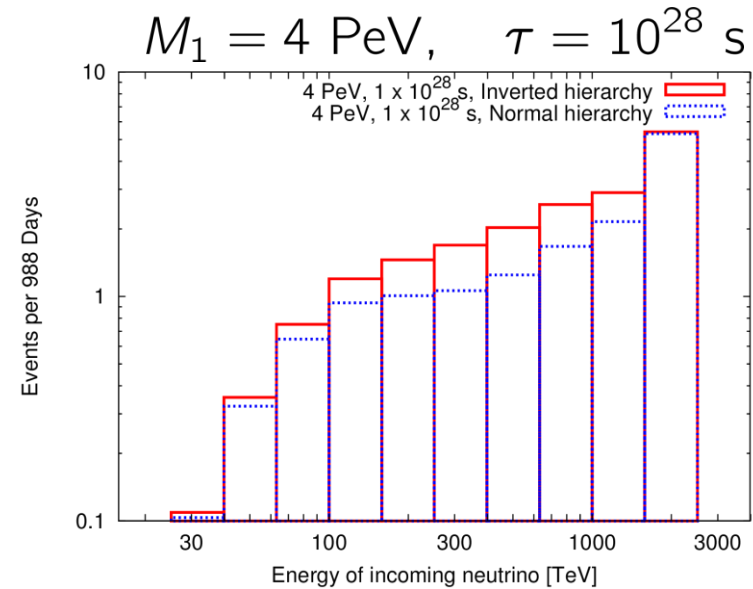
- Extra galactic contribution

$$\frac{d\Phi_{\text{eg}}}{dE_\nu} = \frac{\Omega_{\text{DM}} \rho_c c}{4\pi M_1 \tau_{N_1}} \int_0^\infty \frac{dz}{H(z)} e^{-s(E_\nu, z)} \frac{dN_\nu}{dE_\nu} \Big|_{E=(1+z)E_\nu}$$

# Number of events



[arXiv : 1405.5303]



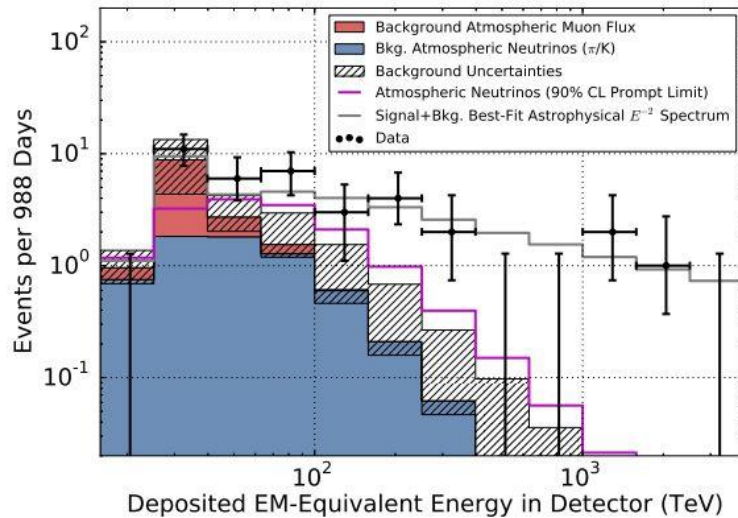
For Normal hierarchy,

$$N(30 \text{ TeV} \leq E_\nu) = 9.7 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 22 \times \left( \frac{\tau_{N_1}}{0.44 \times 10^{28} \text{ s}} \right)$$

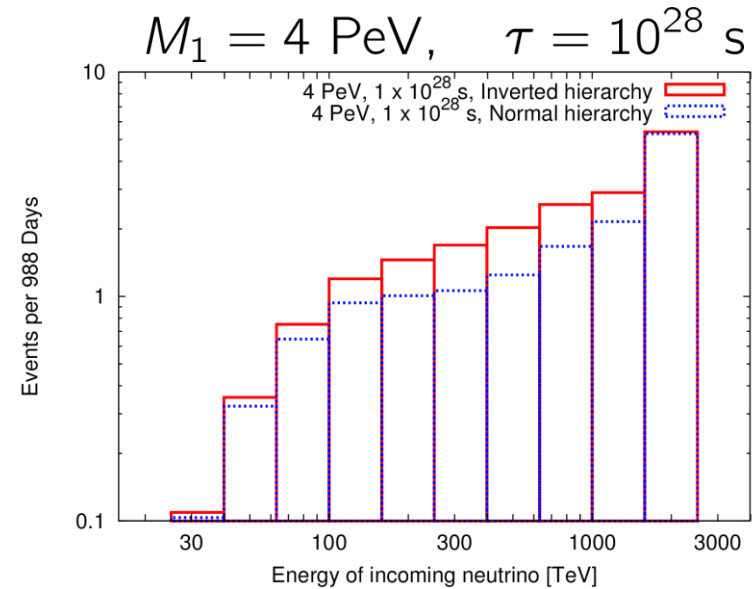
$$N(1 \text{ PeV} \leq E_\nu) = 5.0 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 3.0 \times \left( \frac{\tau_{N_1}}{1.6 \times 10^{28} \text{ s}} \right)$$

PeV dark matter with its lifetime to be around  $10^{28} \text{ s}$   
can explain the event excess at the IceCube experiment.

# Number of events



[arXiv : 1405.5303]



For Inverted hierarchy,

$$N(30 \text{ TeV} \leq E_\nu) = 12.4 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 22 \times \left( \frac{\tau_{N_1}}{0.56 \times 10^{28} \text{ s}} \right)$$

$$N(1 \text{ PeV} \leq E_\nu) = 5.6 \times \left( \frac{\tau_{N_1}}{10^{28} \text{ s}} \right) = 3.0 \times \left( \frac{\tau_{N_1}}{1.9 \times 10^{28} \text{ s}} \right)$$

PeV dark matter with its lifetime to be around  $10^{28} \text{ s}$   
can explain the event excess at the IceCube experiment.